Forest Research Report No. 160

Utilization of Genetically Improved Stock to Increase Carbon Sequestration

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Utilization of Genetically Improved Stock to Increase Carbon Sequestration

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Abstract

Changes in moisture and temperature regimes caused by global warming are expected to cause a major redistribution of species, species complexes, and populations within species. Accurate predictions of future forest dynamics affecting carbon sequestration will not be possible unless these impacts are accounted for. Older provenance trials are ideal for providing information on adaptation and responses to environmental change.

The 410-series rangewide white spruce (*Picea glauca* [Moench] Voss) provenance trial, which was established at numerous test sites about 25 years ago, served as the base material for investigating potential effects of climate change at the species and population levels. Growth and survival data were obtained from 21 test sites (15 in Ontario, 3 in Nova Scotia, and 3 in Maine). Numerous climatic variables were interpolated from the Ontario Climate Model v. 2 for each of the Ontario sites; values were also provided for sites outside Ontario. Population response functions using quadratic equations predicted the optimal temperature or precipitation to produce best growth and survival for each of the 141 populations tested on at least 4 study sites.

Mean maximum January temperature and mean May precipitation, which showed strong relationships with growth and survival, were used to predict optimal habitats for every population. Predictions were made for the present and for 50 years into the future, based on global circulation model projections for Ontario. Optimal habitats were expected to shift north by about 2° latitude, although patterns were different for certain populations. Under predicted climate change scenarios, populations will survive at their present locales, but productivity will be curtailed.

Acknowledgements

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Introduction

Climate change is expected to cause many changes in Canada's forests, and even small changes in climate might be expected to affect plant growth and survival. In Ontario, global warming predictions point to increases in mean annual temperature (particularly in the northwestern and southern regions), change in moisture patterns, and increased frequency of extreme weather events (Colombo et al. 1998).

Such changes in climate might have numerous consequences for plant and animal species. For example, migration rates in response to environmental pressures differ per species, causing the breakdown of current species associations and formation of new species assemblages. Tree species in particular are expected to demonstrate slower adaptational response because of their longevity and time required to reach reproductive maturity.

Within species, populations may differ in their responses to various climatic variables, in the habitats that they are able to occupy, and in the breadth of habitats suitable for their survival and growth. Rehfeldt et al. (1999) suggested that a major redistribution of tree species and genotypes across the landscape may be needed to maintain forest productivity, health, and biodiversity should climate change scenarios be realized.

Those individuals that may be best suited to the environment at time of establishment may not be the same individuals most suited to their altered environment at maturity. The ability to accurately account for carbon will be seriously jeopardized unless these impacts are taken into consideration and accounted for.

Rangewide provenance studies are typically long-term experiments in which populations from across a species' distribution are tested on sites that sample the species' range. Hence provenance trials provide valuable information on adaptation and responses to environmental change and are ideal for predicting and quantifying impacts of climate change at both species and population levels.

Trial data may be used in conjunction with climate models that characterize climatic variables for each population and site. Response functions can be used to predict growth and survival of a population in relation to environmental gradients. Predicted changes in climatic variables based upon general circulation models may then be superimposed for making predictions about future optimal habitats.

This study was designed to investigate potential impacts of climate change and to explore the potential for seed source movement in current and future reforestation efforts using a previously established white spruce (*Picea glauca* [Moench] Voss) provenance trial. White spruce is particularly well suited to such studies because it has a widespread, mainly contiguous range, is able to thrive under a range of environments, and is known to contain high levels of genetic variation. Many traits measured in this species exhibit clinal variation in response to environmental gradients. Better characterization of the pattern of white spruce adaptive variation has direct implications for both reforestation and carbon sequestration in Ontario.

Methods

During the late 1970s and early 1980s, a rangewide white spruce trial, known as the 410-series, was established across the species' range with seed collections from over 300 rangewide sources. Not all populations were well-represented across all sites. Since the provenance trials focused on the southern part of white spruce's range where it is most important commercially, certain populations were not tested near their niche limits, reducing the accuracy of characterization of population limits to growth and survival.

Fifteen test locations were installed in Ontario by the Canadian Forest Service (CFS) and Ontario Ministry of Natural Resources (OMNR) (Figure 1). Morgenstern and Copis (1999) summarized early results from the Ontario sites installed by the CFS, although only a subsample of seedlots had been measured per site.

Test designs were not uniform at all sites, but all were randomized complete block designs with between 5 and 8 blocks per site. At most sites, provenances were established in row-tree plots (5 to 10 trees per row), although single-tree plots were also used at some sites. Test sites were not maintained beyond the late 1980s. Frost and pest damage and competition invasion were experienced at some sites post establishment, and the Thunder Bay site was partially burned by wildfire.

Every provenance at all of the Ontario sites was completely remeasured for growth and survival in the summer of 2001 (Table 1). Data from 3 Nova Scotia sites and 3 Maine sites from the same rangewide series were provided for this project by D. Simpson and P. Copis, CFS. Diameter was not measured at the Maine test sites. Tree height and diameter for all 21 sites were adjusted to the average test age of 24 (adjht). To

Figure 1. White spruce 410-series provenance trial Ontario test sites and seed sources.

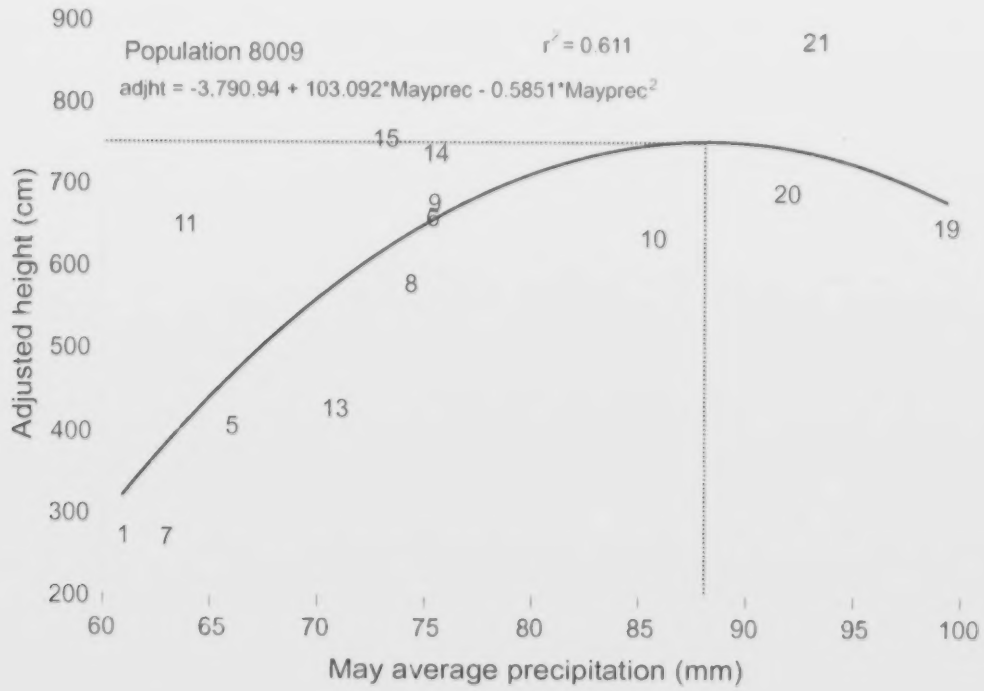

Figure 2. Population response function of adjusted height regressed against May average precipitation, where average performance at each test site is represented by corresponding test site numbers (listed in Table 1).

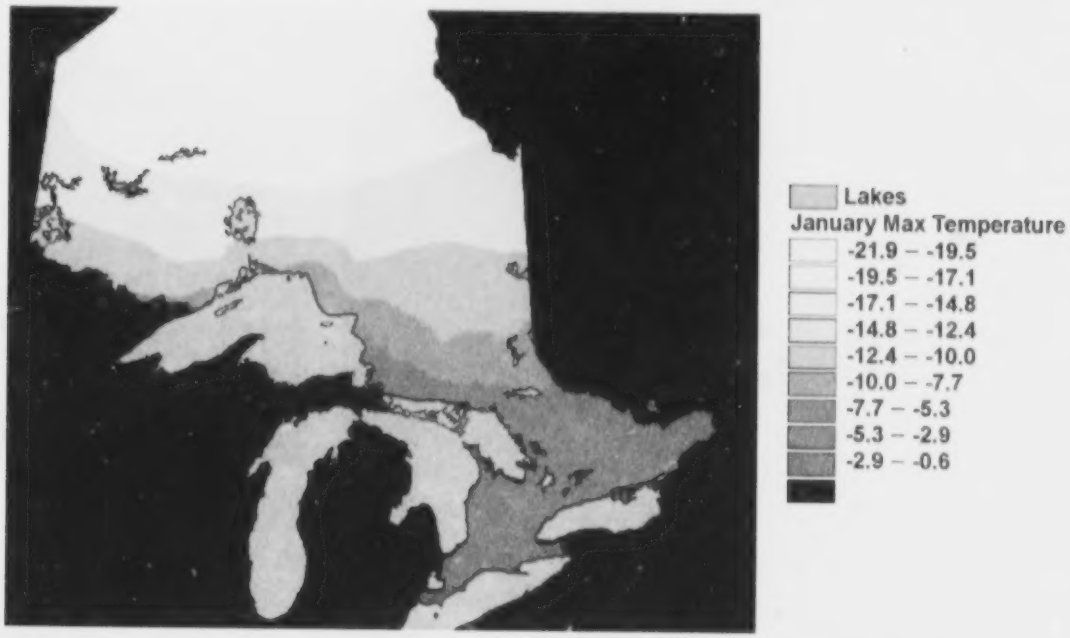

Figure 3. Average January daily maximum temperature (C) based on 1961-1990 norms (source: OMNR 2000).

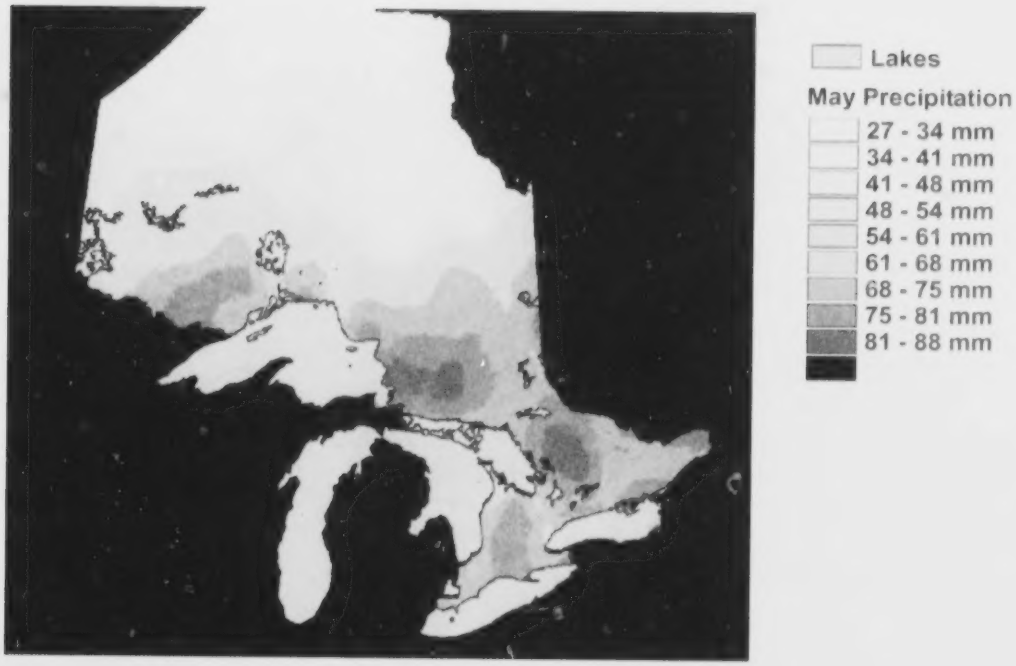

Figure 4. Average May accumulated precipitation (mm) based on 1961-1990 norms (source: OMNR 2000).

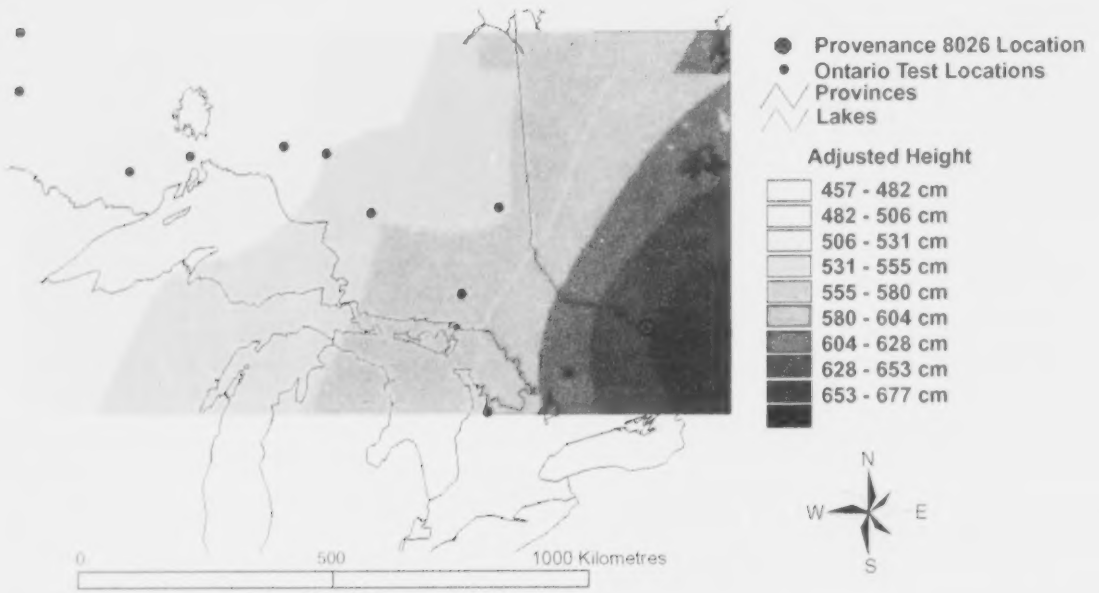

Figure 5. Mean adjusted height per test site for population 8026, Beachburg/Forester Falls, Ontario.

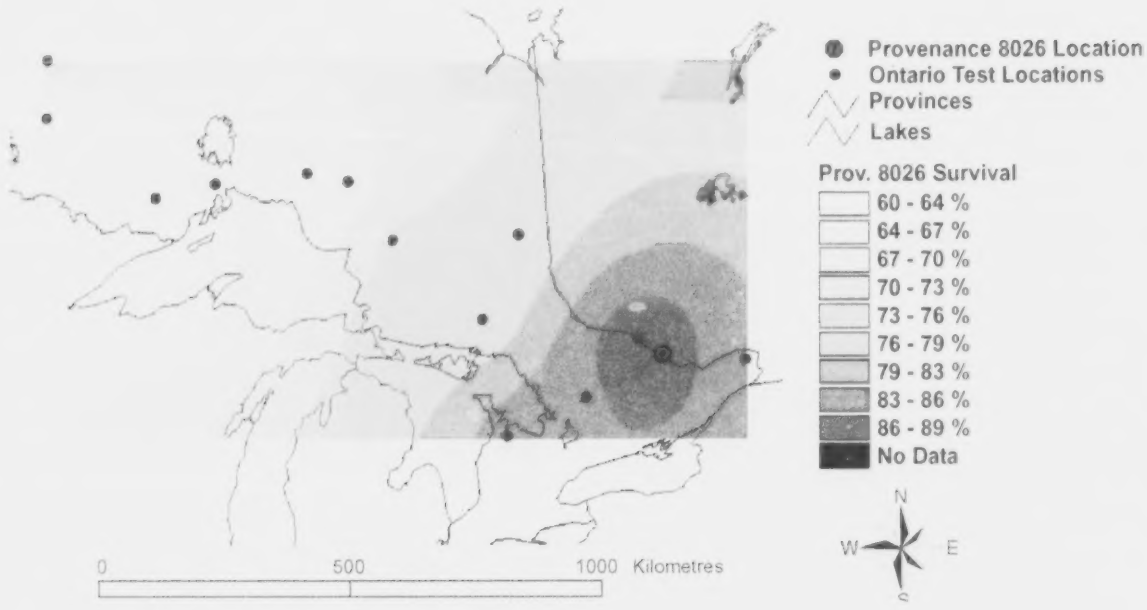

Figure 6. Mean adjusted survival % per test site for population 8026, Beachburg/Forester Falls, Ontario.

Figure 7. Predicted optimal January average maximum temperatures and May average accumulated precipitation for the periods 1961-1990 and 2040-2069 for population 8009, Erin Township, Quebec.

Figure 8. Predicted optimal January average maximum temperatures and May average accumulated precipitation for the periods 1961-1990 and 2040-2069 for population 8009, Erin Township, Ontario.

Figure 9. Predicted optimal January average maximum temperatures and May average accumulated precipitation for the periods 1961-1990 and 2040-2069 for population 8010, Mulmur Township, Ontario.

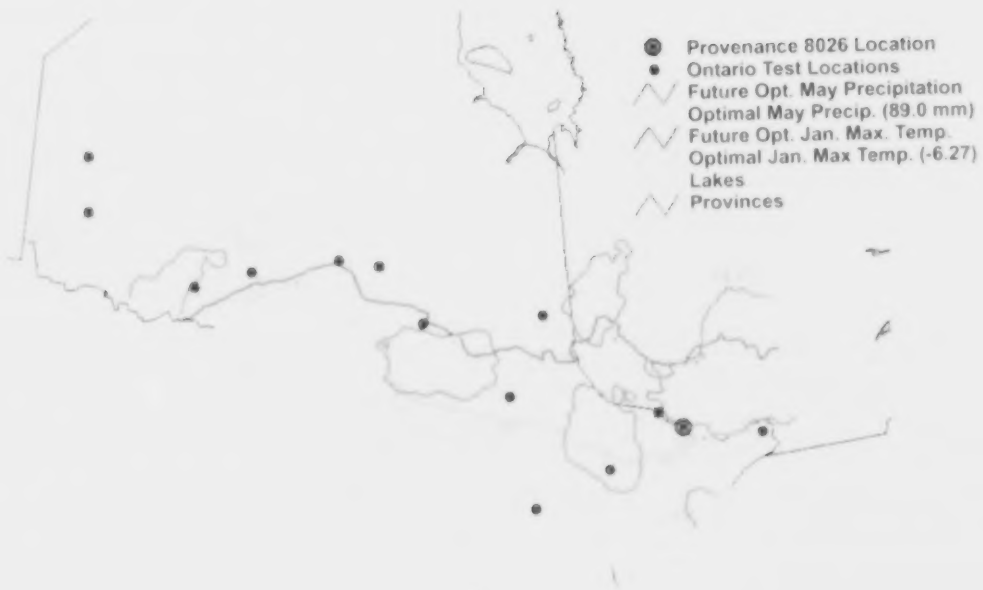

Figure 10. Predicted optimal January average maximum temperatures and May average accumulated precipitation for the periods 1961-1990 and 2040-2069 for population 8026, Beachburg/Foresters Falls, Ontario.

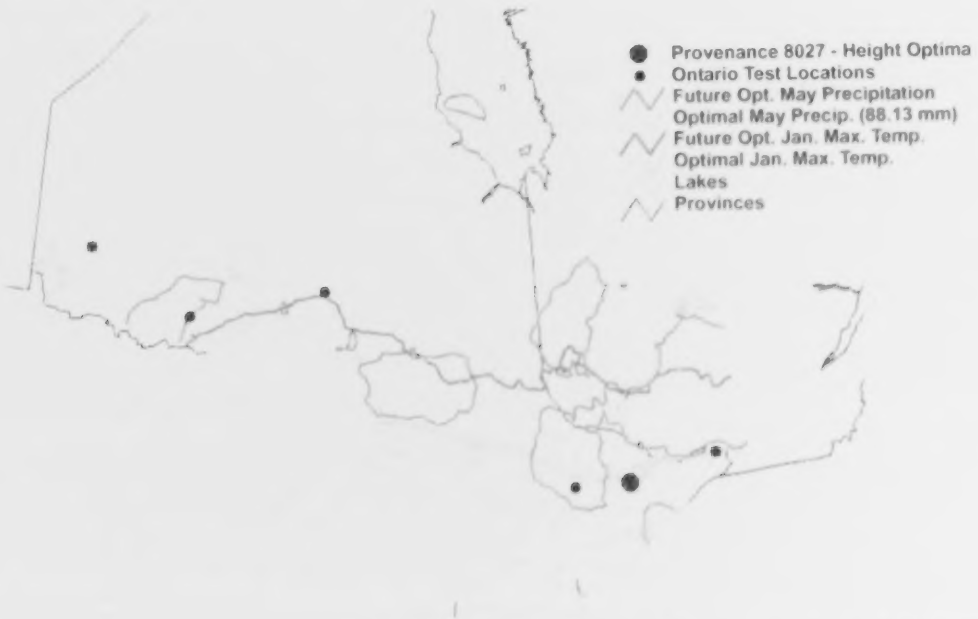

Figure 11. Predicted optimal January average maximum temperatures and May average accumulated precipitation for the periods 1961-1990 and 2040-2069 for population 8027, Irvine Lake, Ontario.

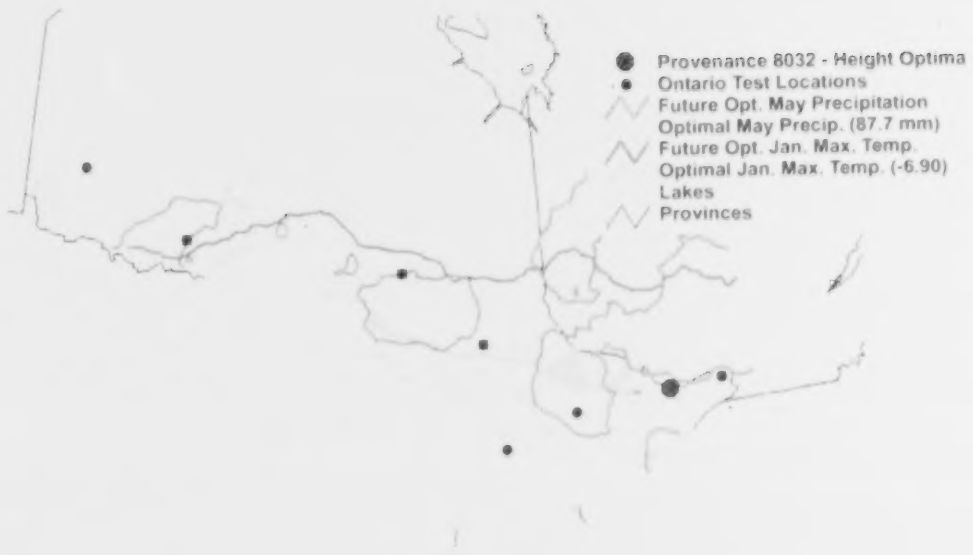

Figure 12. Predicted optimal January average maximum temperatures and May average accumulated precipitation for the periods 1961-1990 and 2040-2069 for population 8032, Antrim, Ontario.

Figure 13. Predicted optimal January average maximum temperatures and May average accumulated precipitation for the periods 1961-1990 and 2040-2069 for population 8033, Mowatt Township, Ontario.

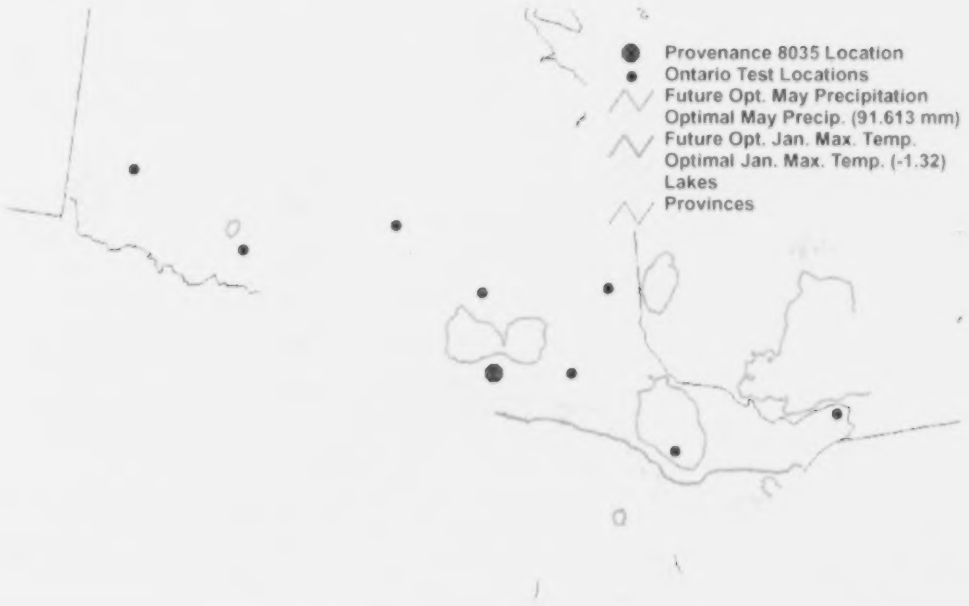

Figure 14. Predicted optimal January average maximum temperatures and May average accumulated precipitation for the periods 1961-1990 and 2040-2069 for population 8035, Snowshoe Flats, Ontario.

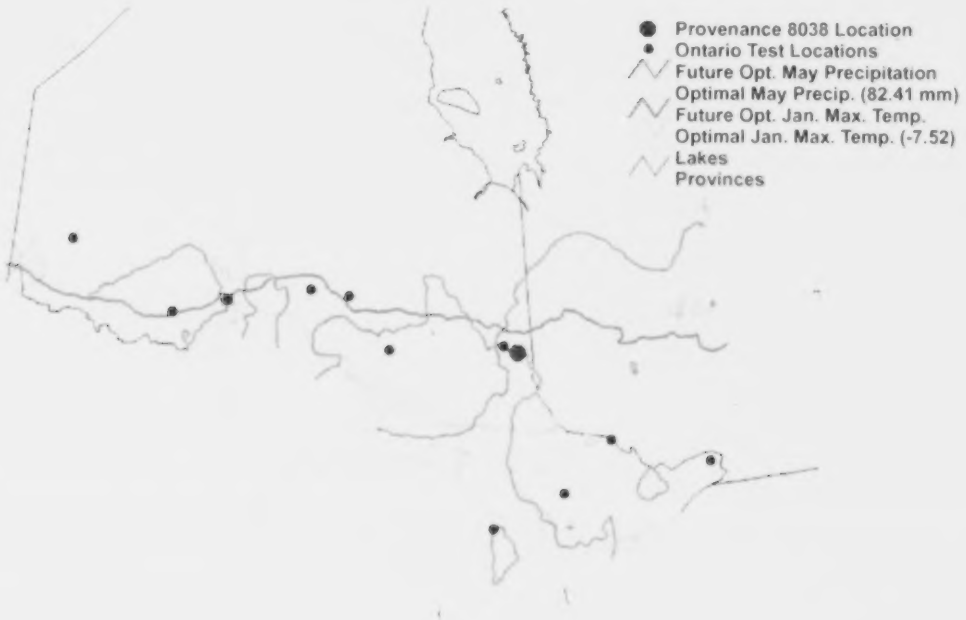

Figure 15. Predicted optimal January average maximum temperatures and May average accumulated precipitation for the periods 1961-1990 and 2040-2069 for population 8038, Englehart, Ontario.

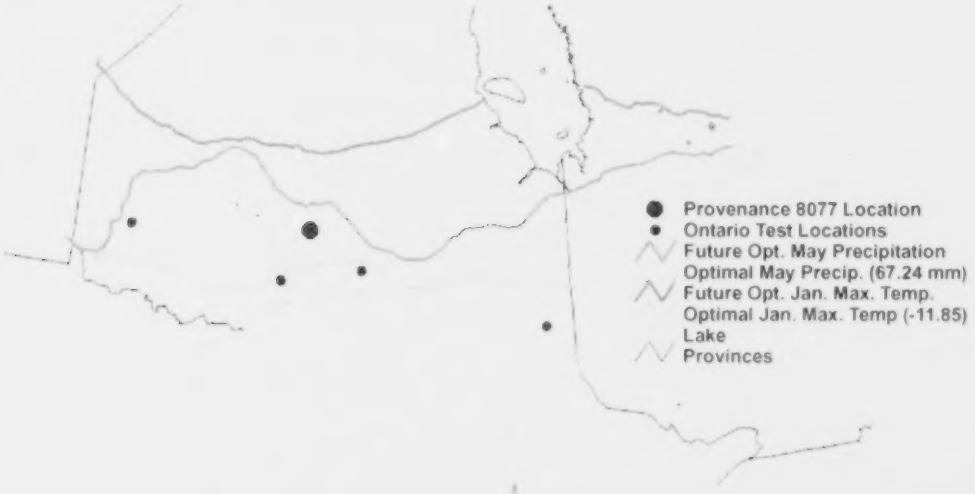

Figure 16. Predicted optimal January average maximum temperatures and May average accumulated precipitation for the periods 1961-1990 and 2040-2069 for population 8077, South Onaman River, Ontario.

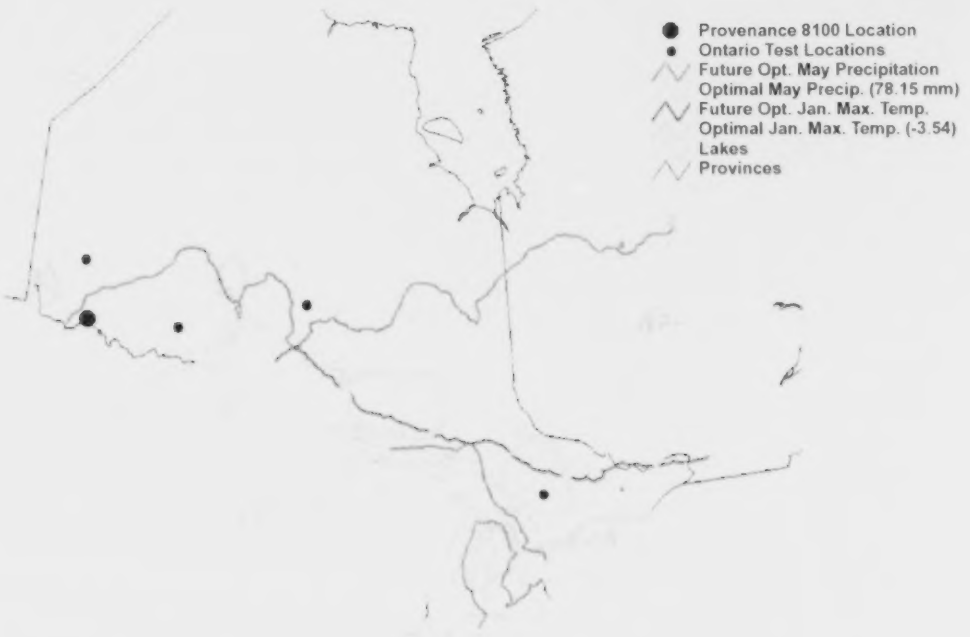

Figure 17. Predicted optimal January average maximum temperatures and May average accumulated precipitation for the periods 1961-1990 and 2040-2069 for population 8100, Rainy Lake, Ontario.

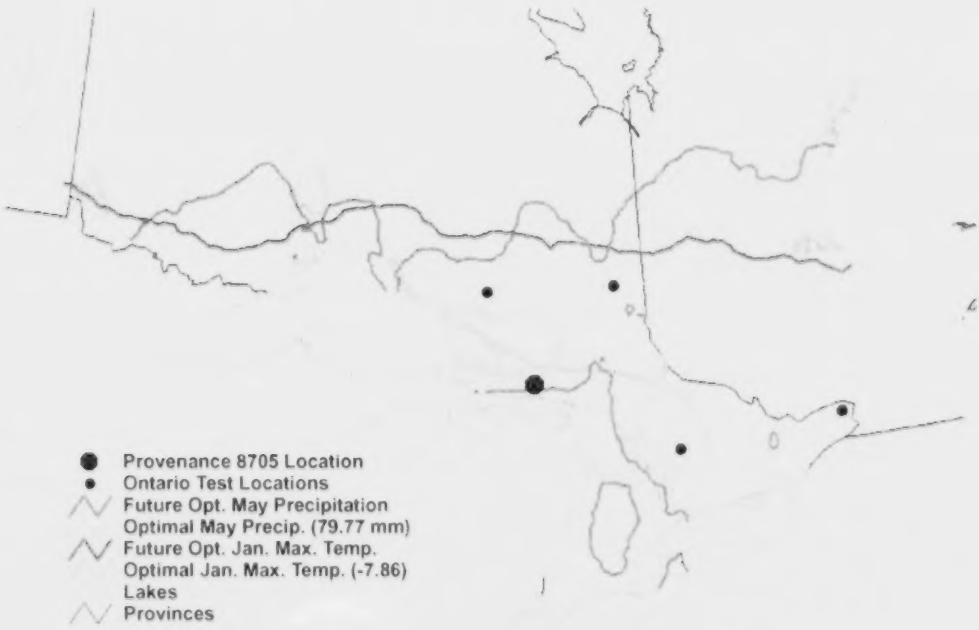

Figure 18. Predicted optimal January average maximum temperatures and May average accumulated precipitation for the periods 1961-1990 and 2040-2069 for population 8705, Proctor Township, Ontario.

mitigate design differences among sites and to adjust for tree mortality, plot mean values were calculated and used for further analysis.

In cases where only one plot mean was available per seed source at a particular test, it was removed from further analysis. After removal of populations of unknown origin and those resulting from the bulking of seedlots from different locations, a total of 263 populations from throughout the entire range remained.

Genetic variability was examined via standard methodologies. Analysis of variance (ANOVA) was carried out to determine if populations differed, using the model:

$$Y_{ijk} = \mu + Loc_i + Prov_j + Loc*Prov_{ij} + \varepsilon_{(ij)k} \quad [1]$$

where provenance (Prov) and site (Loc) effects were considered to be random.

Intraclass correlation coefficients were estimated as follows:

$$r_1 = \frac{\sigma^2 Prov}{\sigma^2 Prov + \sigma^2 Prov*Loc + \sigma^2 E} \quad [2]$$

Using the Ontario Climate Model v. 2.0 (OMNR 2000), a broad suite of climatic variables was generated for every Ontario population and test site; values were also provided for sites outside Ontario (McKenney 2002, Can. For. Serv., pers. comm.). Climatic and geographic variables investigated included latitude, longitude, elevation, mean monthly average daily minimum and maximum temperatures, mean monthly precipitation, mean annual temperature and precipitation, growing degree days (5°C base), difference between July and January average monthly temperatures, and ratio of mean annual temperature to mean annual precipitation.

Quadratic regression models of the following form were used to relate growth and survival (Y) to a number of climate variables (X):

$$Y_{ij} = \beta_0 + \beta_1 X_j + \beta_2 X^2{}_j + \varepsilon_{ij} \quad [3]$$

To develop individual response functions by population, only those populations present on at least 4 sites could be utilized; 141 populations met this criterion. A response function approximating the fundamental niche

Table 1. Summary of actual site mean height, diameter, and survival in 2001 at 21 white spruce 410-series provenance test sites.

Site		Latitude	Longitude	Elevation (m)	Measurement age[1]	Height (cm)	DBH (cm)	Survival (%)
1	Dryden	49°54.4'	93°19.8'	410	26	258.14	3.41	68.40
2	Fort Frances	48°45.3'	93°57.5'	340	28	361.25	5.20	88.39
3	Kenora	50°07.7'	93°49.9'	410	28	557.39	7.76	92.82
4	Red Lake	50°56.1'	93°28.7'	370	21	491.73	8.57	90.31
5	Nipigon	48°57.9'	88°31.8'	190	26	402.64	6.11	84.75
6	Thunder Bay	48°38.2'	90°08.5'	475	26	663.63	9.32	65.66
7	Manitouwadge	49°11.9'	86°01.0'	300	26	297.31	4.60	6.47
8	Sudbury	46°31.0'	81°24.0'	350	24	486.93	6.41	72.10
9	Chapleau	47°59.4'	83°41.8'	451	25	662.64	8.60	82.14
10	Minden	45°00.4'	78°52.9'	376	25	580.86	7.55	79.97
11	Hearst	49°04.0'	84°53.1'	320	21	633.46	10.53	64.67
12	Kirkland Lake	48°00.0'	80°19.8'	308	19	355.96	4.41	71.07
13	Owen Sound	44°23.9'	80°54.8'	200	22	373.18	5.10	86.83
14	Cornwall	45°22.3'	74°44.3'	24	23	710.85	11.86	85.76
15	Chalk River	45°59.0'	77°26.0'	170	20	687.50	11.75	93.87
16	N.S. Georgefield	45°09.0'	63°34.0'	110	13	593.40	7.65	87.35
17	N.S. Scotsburn	45°39.0'	62°51.0'	110	13	501.90	5.43	89.27
18	N.S. Maple Brook	45°48.0'	61°16.0'	90	13	275.13	1.96	97.71
19	Maine Woodland	45°15.0'	67°30.0'	60	20	663.84	-	94.78
20	Maine Ragmuff	46°05.0'	69°35.0'	335	21	728.10	-	73.36
21	Maine Orneville	45°10.0'	69°00.0'	150	20	851.50	-	93.62

[1]Year measured = 2001 for sites 1 to 15; 1990 for sites 16 to 18; 1997 for sites 19 and 21; 1998 for site 20

across a climatic gradient was developed for each population for every climatic variable. The models were also used to predict the point at which maximum performance can be attained for every population climate variable combination and to estimate transfer distance to obtain optimal performance for each population. Figure 2 depicts a typical response function generated for one population.

Updated regional global circulation models that will accurately predict how Ontario's climate may change over the next 50 to 100 years continue to be developed. The predictions developed by Bootsma and McKenney (2001), based upon the Canadian Coupled Global Climate Model 2 climate simulations for the period 2040 to 2069, were considered to be the best available for Ontario at present. Seasonal temperature and precipitation expectations for this period are depicted in Cherry (2001).

For the purpose of this study, it was assumed that average annual, summer, and winter temperatures in Ontario will rise by approximately 3°C over the next 50 years. Summer precipitation is expected to decrease by as much as 10% in the region between Thunder Bay and the Manitoba border, as far north as Red Lake, and in southwestern Ontario over the next 50 years. The latter area is roughly bounded by the region from Windsor to Toronto northward through North Bay to the Quebec border, north to James Bay, then southwest to Sault Ste. Marie. The remainder of the province is expected to experience increased precipitation up to 10% above current norms, except near the James Bay coast, which may be subjected to increases of up to 20%.

ArcView was used to map current optimal growth temperature and precipitation from the most recent digital temperature and precipitation grids for Ontario with a resolution of ca. 1 km (Figure 3 and Figure 4). Future optimal temperature and precipitation per population were determined by ArcView from the grids provided by Bootsma and McKenney (2001) for 2040 to 2069 resolved to 15 km.

Results

Provenance differentiation varied greatly across the 21 test locations, as observed by ANOVA ($p < 0.0001$ for adjusted height, adjusted diameter, and survival). Figure 5 exemplifies the mean adjusted height of one population (Beachburg Foresters Falls, Ontario) across all sites at which it was tested, while Figure 6 shows average survival per test site for the same population. Both height and survival of population 8026 demonstrated clinal variation, with best performance at the eastern test sites. This region, characterized by limestone soils, is known for its high growth potential for white spruce limestone ecotypes (Morgenstern and Copis 1999; Teich and Holst 1974) such as population 8026.

Table 2. Geographic location, number of test sites, overall adjusted height, average January maximum temperature and May precipitation, and predicted optimal January maximum temperature and May precipitation for best height growth of 12 selected populations of white spruce.

Population	° Latitude	° Longitude	Elevation (m)	# test sites	Overall adjht (cm)	Provenance Jan. max. temp °(C)	Predicted optimal Jan. maxt.	Provenance May prec. (mm)	Predicted optimal May prec.
8003	46'35'	75'10'	243	8	629.27	-7.90	-5.37	90.13	84.08
8009	43'44'	80'06'	411	14	603.69	-4.46	-6.60	74.70	86.72
8010	44'14'	80'04'	396	8	564.59	-3.45	-7.30	67.94	91.52
8026	45'41'	76'48'	137	19	596.92	-6.53	-6.27	76.48	88.95
8027	45'01'	77'16'	300	11	544.60	-6.21	-6.19	74.66	88.13
8032	45'19'	76'11'	121	13	606.13	-6.06	-6.90	72.29	87.72
8033	45'54'	80'26'	213	7	638.99	-6.09	-6.76	71.48	86.43
8035	46'35'	83'24'	365	8	475.08	-6.31	-1.32	77.57	91.61
8038	47'52'	79'55'	215	11	571.90	-10.14	-7.52	69.68	82.41
8077	50'02'	87'39'	305	4	310.34	-13.67	-11.85	63.11	67.24
8100	48'42'	93'03'	336	4	429.95	-10.96	-3.54	68.55	78.15
8705	46'20'	82'30'	249	4	567.51	-6.25	-7.86	76.59	79.77

Intraclass correlation coefficients for adjusted height ($r_i = 0.140$) and adjusted diameter at breast height ($r_i = 0.150$) were relatively high, while intraclass correlation coefficients for survival was low ($r_i = 0.028$). In concurrence with earlier analyses of some sites and seed sources (Morgenstern and Copis 1999), southern provenances typically exhibited better growth than local sources when moved north.

The modelled patterns of predicted seed source 'optimal' growth and climate values showed that performance rises, achieves a maximum, and falls following a south to north transect through Ontario. The pattern emerging from the response functions is that northern populations perform best with a transfer to warmer climates, while southerly populations perform best when transferred to somewhat cooler climates.

Population response functions accounted for up to 90% of observed variation. However, the strength of the regression coefficient was dependent in part on the number of sites at which a population was tested, with sources tested at fewer sites exhibiting stronger relationships.

The strongest and most consistent relationships between growth and climate were observed with the variables average January maximum temperature (Jan. maxt., Figure 3) and average total May precipitation (May prec., Figure 4). Midwinter cold temperatures are limiting factors to white spruce growth. Precipitation during the period just prior to shoot elongation also influences growth. These 2 variables were therefore selected to represent the response to temperature and moisture gradients.

Population differences in survival were not large enough to detect the consistent patterns observed with growth, although the above variables also influenced survival to a lesser degree.

Present and future growth optima are mapped in figures 7-18. These figures depict predicted optimal January maximum temperatures and predicted optimal May precipitation for the periods 1961-1990 and 2040-2069 for 12 selected populations. The populations chosen for illustration are representative of response functions obtained (Table 2, Table 3). Where optimal present precipitation is not depicted on a map (populations 8010, 8026, 8027, and 8035), the predicted optima for those populations are outside of Ontario to the east or south.

All selected populations produced an optimal climatic value that resulted in the prediction of an optimal adjusted height for the population. Where possible, populations that were represented on numerous sites and that represented various locations from around Ontario were desired. However, southern Ontario populations were better-represented than northern populations.

Table 3. Mean adjusted height at each test site for 12 selected populations of white spruce.

Site	8003	8009	8010	8026	8027	8032	8033	8035	8038	8077	8100	8705
1	261.35	272.42	196.16	283.72	236.80	220.99	224.27	241.49	301.61	255.14	252.94	
2												
3												
4				472.61								
5	451.10	407.45		434.58					471.56	402.98		
6		659.85	581.34	758.74	708.57	774.90	677.72	605.35	568.40		678.06	
7		270.43		271.57	228.55			302.73	392.49	265.79	285.52	
8	588.04	578.20		577.95		521.42		537.96				
9		675.20		639.65		701.92		568.44	752.93			688.45
10		634.10	496.55	652.96	539.81	668.64	654.45	644.21	651.35		581.82	566.85
11	717.69	650.27		705.01					672.95			
12				376.96				373.73	420.98	307.82		348.56
13		427.92	354.14	492.53		467.25			397.38			
14		736.89	733.54	824.59	716.53	825.55	755.67	621.07	740.25			649.61
15	737.73	754.36		722.48					712.41			
16				652.33	575.32	644.71						
17				605.18	582.26	534.16						
18				319.96	276.46	274.72						
19	593.70	647.75	638.39	708.50	662.82	690.87	652.48					
20	641.14	689.91	714.39	776.62	727.76	696.87	737.55					
21	835.68	873.20	841.60	943.20	770.20	810.40	777.60					

Very similar patterns were produced for current and future optimal January maximum temperatures and predicted optimal May precipitation for populations 8003, 8009, 8026, 8027, 8032, and 8033 (figures 7-8 and 10-15). For these populations, current optimal habitat based upon January maximum temperature followed an isotherm stretching from the Sault Ste. Marie vicinity along the north shore of Lake Huron and east to Chalk River (ranging from -5.4 to -6.9°C). Four of the 6 populations (8026, 8027, 8032, and 8033) coincided with current temperature-based optima; one source (8003) coincided with the future temperature-based optimum; one source (8009) was located far south of both current and future temperature-based optima.

Future predicted habitat for the above 6 populations, assuming a 3°C increase in winter temperatures by 2050, would be about 1 to 2° latitude north of the current optima. Future optimal habitat based on May accumulated precipitation appears to be more widespread within Ontario than at present and generally depicted similar areas for optimal habitat as those derived from temperature.

Populations 8010, 8038, and 8705 exhibited temperature-based optima that were slightly colder (-7.3 to -7.9°C) than those of the 6 former populations (figures 9, 15, and 18). This isotherm ran along the eastern shore of Lake Superior, through the Wawa region, and east to North Bay. Predicted future temperature-based optima roughly coincided with 49°30' latitude, indicating a shift of about 2 to 3° north over the next 50 years. While population 8038 was located just south of the future predicted temperature-based optima, populations 8010 and 8705 were located slightly south of the current temperature-based optima. Again, optimal precipitation appeared to be more widespread, at least within Ontario, under future conditions and more or less coincided with temperature-based optima.

Population 8035 is located further north than both the current (shores of Lake Ontario) and future (north shore of Lake Huron to Kingston) temperature-derived optima, while future precipitation-derived optima are located sporadically for this population (Figure 14).

The Rainy Lake population (8100, Figure 17) is further northwest than current and future temperature-based optima and the current precipitation-based optimum but is adjacent to the predicted future May precipitation-based optimum. For this population, temperature and precipitation optima do not overlap in space, although both estimates predict that best habitat for this population will shift northward under expected future conditions. This population, which is from a warmer northern climate, responded in a similar manner to a southern Ontario population.

Population 8077 (Figure 16) is located slightly north of predicted current temperature and precipitation-based optima but south of future optima for both variables. While current optima estimated by temperature coincided with that estimated by precipitation, future optima estimated by temperature (about 53° latitude) was much further north than that estimated with precipitation.

Discussion

Featured populations are unintentionally biased towards southern Ontario. While the limits to growth of the southern populations were well sampled by the environmental conditions at the northern test sites, these northern sites were not climatically extreme enough to approach limits to growth for the northern populations. Therefore, northern populations in many cases did not produce reliable response functions.

For the majority of the featured populations, current optimal growth occurs between about 45° and 47° latitude, in a band parallel to and slightly north of the north shore of Lake Huron, running eastward through the region between North Bay and Chalk River and into Quebec. The optimal habitat for populations 8035 and 8100 is located in southern Ontario near lakes Ontario and Erie, while that of population 8077 is in northern Ontario around 49° latitude.

If average temperature and precipitation are altered over the next 50 years due to climate change according to today's estimates, the optimal habitat for these white spruce populations will shift northward by about 1° to 3° latitude. While future local habitat conditions for populations 8003, 8035, 8038, and 8100 appear to be enhanced over current conditions, the remainder of the profiled populations are expected to experience less suitable climates than at present. While the latter populations will be able to survive in their current habitat, growth will be reduced, and trees will not reach their full potential.

Estimates of potential habitat shifts are only as reliable as the available climate circulation models. These predicted shifts are probably more reliable when based upon temperature rather than precipitation, due to the high degree of uncertainty surrounding currently

available estimates of changes in precipitation within Ontario due to climate change. Until a regional-scale climate circulation model becomes available for Ontario, particularly one that can model effects of the Great Lakes on local climate patterns, future climate predictions have a high degree of uncertainty.

The results of this study underline the need to consider multiple climatic factors when predicting future habitats for white spruce and other forest tree species in Ontario. Optimal temperatures for a population's growth will not be beneficial and may even produce negative consequences, unless optimal or near optimal levels of precipitation are also present. Our results suggest that this situation will be more problematic for northern Ontario sources such as population 807 7 than for more southerly Ontario sources.

Conclusions

Based upon response functions developed from a white spruce provenance trial, optimal habitats for Ontario populations are expected to shift northward by approximately 2° if the climate changes as expected. While populations will likely survive in their current locales, productivity would be expected to be much curtailed under climate change. This has large implications for forest management plans, which to date have not considered the possibility of reduced growth and yield due to maladaptation of seed sources resulting from climate change. Further, carbon sequestration rate estimates would need to be adjusted downward due to slower growth.

Potential management strategies for mitigation of these effects include changing the way that seed sources are selected for planting sites. Because extreme weather events and compounding factors such as occurrence of damaging fall or spring frosts have the ability to cause widespread mortality, these factors must not be ignored.

A potential strategy might be to use half of the expected shift in optimal habitat, or 1° latitude, as a transfer distance for seed sources. Under this scenario, sources would be planted 1° north of current planting prescriptions. Seed sources would then be growing in a habitat midway between current and future optimal habitats.

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